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Qualities of uncoated groundwood paper affecting adhesive binding strength

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QUALITIES OF UNCOATED GROUNDWOOD PAPER AFFECTING ADHESIVE BINDING STRENGTH

by
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CERTIFICATE OF APPROVAL

MASTER'S THESIS

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with a major in Printing Technology has been approved by the Thesis Committee as satisfactory for the thesis requirement for the Master of Science degree at the convocation of May, 1981

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ABSTRACT

This investigation has examined the adhesive binding of paper, with particular attention to the action of the fiber/adhesive interface. The efforts of this research were concentrated on relating properties of the paper to strength of the resultant binding. To simulate the problems of economical binding styles, uncoated groundwood paper and hot melt adhesives were studied.

Although the hypotheses assumed that a strong interfiber bond within the sheets would lead to a strong binding, it was found that the most critical factor was not the strength of the sheet, but the availability of the fibers to the adhesive.

The strength of the sheet was measured by several tests. These tests were: tensile strength, internal bond, tear resistance, and pick resistance. None of these measures of paper strength correlated with binding strength. Other factors, specifically caliper, absorbency, and low pick resistance proved to be the significant factors leading to a strong binding. The general conclusion is that the greater the surface area of the fibers exposed to the glue, the greater the adhesive bond. Greater caliper, absorbency, and low pick resistance lead to increased exposure of fibers and therefore to a stronger binding for newsprint-grade papers. Previous studies with both

coated and uncoated papers had indicated that roughness is the most important paper quality for a good binding with hot melt adhesives. This study finds that roughness is not a significant factor, and the thickness and low pick resistance are the most significant factors leading to a good binding with uncoated groundwoods.

Acidity was tested for effects on binding strength. Even with accelerated aging, no evidence was found that the acidity of the sheet affects the strength of the adhesive binding.

Binding strength was measured by page pull and flex tests. Both can be valuable tests, and in this case correlated well with each other.

CHAPTER I
INTRODUCTION

The success of an adhesive binding lies in that narrow strip of the spine where the pages meet the adhesive film. The factors affecting that critical paper/adhesive interface may be divided into two broad areas: the adhesive and its application, and the paper and its preparation. The scope of this investigation is limited to the paper itself, specifically to the qualities of uncoated groundwood paper which affect the strength of an adhesive binding.

The paper characteristics investigated were those which were expected to significantly affect the binding. These expectations or hypotheses were based on knowledge of the special properties of newsprint-grade paper, experience in binding testing, and on a model of the action of hot-melt binding derived from previous studies.

The model assumed that the paper fibers which contact the adhesive are bonded to the glue by adhesion more firmly than to the sheet of paper by the interfiber bond. Interfiber bond is a combination of chemical and physical forces by which fibers are secured into a sheet of paper. The fibers are bonded to each other by a chemical bond achieved during the pulping and sheet formation. To a lesser extent, the fibers are bonded by the physical twisting, fraying, and intertwining of the fibers. Adhesion is the surface strength between two different materials which creates a bond (as opposed to cohesion, which is the internal bond within a single substance). Please see Appendix I for a discussion of these forces as they apply to adhesive binding.

According to the model, the interfiber bond is weaker than the adhesive bond between the glue and the fibers. Consequently, when the page is torn out, the sheet "tears" as fibers pull from the sheet and remain in the adhesive film. This original model implies that the strength of a binding is dependent, not on the adhesive qualities of the glue, but on characteristics of the paper.

The purpose of this paper is to identify those characteristics of uncoated groundwood which lead to a strong book binding when the book is bound with adhesives. Again according to the original model, those critical characteristics must be a measure or expression of the interfiber bond. There are many measures of the interfiber bond, including tensile strength, tear resistance, internal bond strength, and pick resistance. Hypotheses about each test of strength were formed, concerning how well each test would measure the sheet strength or interfiber bond. A test which measured an expression of interfiber bond would hypothetically correlate with binding strength.

Further hypotheses to test the model and its assumptions were made, based on evidence from previous studies (which are presented in Chapter II, "Background Material and Literature Review"). The assumption made in the model is that there is adequate contact between the glue and the fibers to ensure adhesion. Hence, binding strength would depend on sheet strength, and binding strength was hypothesized to correlate to sheet strength. A test of this hypothesis would also reveal if some minimum sheet strength were being approached in the use of lightweight uncoated papers. A further discussion of the parameters and hypotheses involved is presented in Chapter III, "Theoretical Basis."

It is appropriate at this point, however, to reveal that the results of this study show that the inherent strength of the sheet is not a critical factor in binding strength. Other sheet characteristics are responsible for the strength of the binding, including caliper, roughness, absorbency, and low pick resistance. (Fiber composition and acidity were also investigated as possible contributing factors.) In general, the critical factor is the bond between the sheet and the adhesive, and more specifically the amount of contact available between the glue and the paper sheet. The evidence and the paper factors involved are discussed in Chapter V, "Results."

Adhesive binding methods have become economically attractive primarily because they are suitable for mass production. The hot-melts in particular can be advantageously used in line with other printing and finishing operations because of the brief time necessary for the glue to set. The PVA glues (polyvinyl acetate) or "cold emulsions" are also seeing increased use in production with the aid of heat tunnels and high frequency drying. Adhesives' potential for mass production has therefore attracted a great deal of attention, and research has led to improved adhesives and a better understanding of the techniques of glue application. Further investigation into adhesives is a problem of chemical composition beyond the scope of this thesis; this investigation concerns itself with the paper factors which affect the way paper and adhesives form a book binding. The findings in this report will hopefully lead to a thorough understanding of the demands made on the adhesive as well as the paper.

Ironically, as adhesives have improved, and while adhesive binding is successfully taking over a greater share of the binding industry, the quality of paper may be declining. The same economic motives that lead to the choice of adhesive binding also demand the use of the most economical paper. As the price of paper rises, driven higher by material costs and environmental restrictions, printers and publishers will be encouraged to use paper of lower basis weights and ever lower quality. Continued investigation is required to maintain the best combination of paper and adhesives.

Literature on the subject of binding testing reveals a number of factors that contribute to binding strength, but no report deals specifically with the uncoated groundwood or newsprint-grade paper used in mass-market paperback binding. "Newsprint grade" is here meant as a general term for uncoated paper of basis weight 25 to 45 pounds and composed largely of groundwood or mechanical pulp. (The basis weight of a paper is the weight in pounds of 500 sheets of the paper, 25 x 38 inches for book paper such as those under study here. See Appendix II for a conversion of basis weight to the metric equivalent, grammage.) The paper used in this investigation are samples of paper actually used for mass-market trade books, catalogs, telephone directories, and newspapers. The factors under investigation, as prescribed by the model and by the distinctive properties of newsprint, are limited to nine: caliper or thickness; tensile strength; internal bond; roughness; tear resistance; pick resistance; acidity (pH); absorbency; and fiber composition.

To interpret the results of the testing, the measurements of each of the paper factors were tested for correlation with binding strength, as measured by two methods: page pull and flex testing. Descriptions of these tests follow in the chapter on summary and conclusions. Briefly, in a preview of the conclusions and as a guide to understanding the aim of this report, it was discovered that factors (such as thickness, low pick resistance, and absorbency) which lead to a better fiber/adhesive bond are more important than any measurements of strength of the sheet itself.

CHAPTER II

BACKGROUND MATERIAL AND LITERATURE REVIEW

There is a great body of literature on adhesive book binding, on the testing of book strength, and on factors contributing to strength of a binding. The scheme behind these studies is to identify the critical components of a book and investigate the variables responsible for the performance of each component. This information is then used to optimize binding methods.

Fundamental investigations, such as Ristimaki's "Faults appearing in books in practical use,"[1] located the critical parts of the book in three distinct regions: the cover, the book block, and the joint between the cover and the block. Limiting the field of investigation to paperback or "perfect" binding narrows our concentration to the book block and the specialized demands made on adhesives and paper.

Adhesives

As outlined in Hot Melt Adhesives,[2] a review of hot melts based on patent literature, the demands on the adhesive are for good bonding and good durability:

> The hot-melt compositions useful for the perfect binding of books serve at least two critical functions. In the first place, they must hold the

> book together during its formation. Secondly, on cooling or setting, hot-melt adhesives must be able to produce spines having good wear potential so as to be capable of preventing the book from falling apart. Wear potential includes the properties of high bonding strength, flexibility, high film strength (tensile strength) and resistance to aging, mold growth, warm flow and cold crack.[3]

Obviously, double duty is required of a hot melt--the adhesive must not only bond the pages in place but also form a tough, flexible film which is itself part of the spine of the book.

Adhesives for the binding industry are generally of three types: animal glues, emulsion adhesives, and hot melts. Animal glues see little use in production compared with the synthetic glues because of poor flexibility. Even though the characteristics of the glue can be tempered by additives, animal glues are still used for more or less specialized applications, such as where its water solubility is required. Animal glues, like hot melts, are heated to become liquid and tacky, but set by drying as well as cooling.

Emulsion adhesives, often called cold emulsions or PVAs, are an emulsion of adhesives in a dispersing agent. The dispersant in this case is water. The particles of PVA (polyvinyl acetate) are surrounded by a protective colloidal coating. When the protective coating breaks down, the adhesive particles join to form a tough film.[4] Usually this breakdown and particle coalescing occurs upon drying, as the water evaporates, but unfortunately can also occur if the water freezes. PVAs are applied "cold" or at room temperature.

They form a very good bond and a strong film, but have two drawbacks due to the water: a long drying time; and a tendency to cause wavy edges on books bound grain short, that is with the grain running perpendicular to rather than parallel to the binding. Heat tunnels using gas heat or high frequency drying can be used to shorten the drying time, enabling the use of PVAs on in-line binding equipment. PVA adhesives are 30-40% water.[5]

Hot melts avoid these problems because they are 100% solid, having no water dispersant. They set by cooling and therefore set in a very short time, enabling hot melt operations to be carried out in line with other production operations. Hot melts are also appropriate because most mass-market paperbacks are bound grain short, and hot melts are less prone to creating troublesome wavy edges along the binding edge. Although binding grain short is not an optimal binding procedure due to openability problems, paperbacks which are printed on web presses are bound grain short due to the special folding requirements of web presses.

Hot melts are made up of four basic ingredients: the polymer, tackifying resins, waxes, and fillers or special additives. The polymer is the basic ingredient which creates the binding--it forms the film and gives strength and flexibility to the binding. According to Tom Batorski of Peter Cooper Corporation, the polymer is EVA (ethylene vinyl acetate) over 95% of the time.[6] The second ingredient, the resins, are extremely sticky when melted and are therefore the ingredient controlling the adhesive ability of the glue. The waxes merely enable the glue to be fluid, as the polymer by itself is extremely viscous even when hot. The fillers may be clay; the additives may be modifiers such as plasticizers.

Hot melts are usually applied between 300 and 400° F. Two glue rollers in the glue pot apply the adhesive to the backbone of the book after spine preparation. Both rollers are partly submerged in the glue, and both have doctor blades that control the film thickness. The first roller actually contacts the spine, to insure penetration into the sheets and between the sheets. The second roller does not contact the spine; the film of glue contacts the spine and the film splits. Finally, a heated backspinning roller, not immersed in the glue pot, levels the glue film and insures an even coating.[7] Before the glue has a chance to cool and set the cover is applied. Thus the whole book binding is nothing more than the pages and a cover, connected by a film of polymeric material which must both bond the sheets and create a spine.

Adhesives bear more study. Simple comparative testing methods are outlined in the Muller-Martini manual, "Perfect Binding: Theory and Principles."[8] They suggest, for users of adhesive products, a series of tests to find the optimum combination of materials: "Entire series of tests can be run to compare products of different glue manufacturers, the types and grades of paper, and the types of roughening. Such a test series provides a clear idea of how optimum quality perfect binding can be achieved with available glues, papers, and types of roughening."[9]

A less empirical approach to the problems of adhesive binding is being carried out in research laboratories, which seem to be more or less geographically located in the Scandinavian countries and the United States. A report on these efforts follows in the section on paper factors.

Paper Factors

To introduce this section, a report by Seija Korhonen ("Factors affecting the strength of a book") should be cited; her findings about the importance of paper factors has a bearing on the significance of this investigation and on the rest of the reports reviewed here. Assuming roughening to be a significant variable contributing to a good binding, Korhonen tested nine different papers, three different adhesives, and five different roughening techniques. The results stated:[10]

> This analysis showed the paper to be the most relevant variable. The differences between the paper groups were much greater than the differences between the groups with different adhesives and roughening. The differences between the books with different roughening were, on the other hand, more significant than the differences between the books bound with different adhesives.
>
> According to these results, the variables can be placed in the following order of decreasing importance as far as their significance for the pull strengths of the leaves is concerned:

1) paper
2) spine roughening
3) adhesive

Armed with this evidence that paper factors outweigh other factors in adhesive binding, we turn to other reports to discover which specific paper parameters are responsible for a good, strong binding. In what may be the seminal work in this area, Daniel Lamb ("The Bindability of Paper with Adhesives"[11]) ambitiously undertook to create an adhesive binding index whereby any paper could be graded as to "bindability." He began by testing to discover which paper factors affected binding strength. He tested three hundred papers, holding binding method constant (using a commercial hot melt and no spine preparation). Upon testing caliper, basis weight, water absorption, tear strength, smoothness, K&N ink absorption, ash content, and degree of curl, he settled on caliper, K&N ink absorbency, smoothness, and porosity as being the significant factors contributing to a good binding. (A "good" binding can be summed up as "strength." The topic of evaluating the strength of a binding is left to the next section.) It should be noted that the direction of Lamb's study was to enable a bindery to predict the bindability of any given paper, rather than to identify the specific properties of paper which contribute to a good binding. Even so, his findings are prtinent to this investigation, especially as other investigators confirm and expand his findings.

Johansson and Mendel-Hartvig ("The effect of paper parameters on the strength of adhesive-bound books"[12]) made a major study to discover which paper factors contributed to binding strength. Thirty-six papers, 26 coated and 10 uncoated, were tested. Each sample was measured for the following characteristics: grammage, thickness, density, roughness (two methods), ash content, K&N ink absorbency, IGT pick test, stiffness, and folding endurance. Both hot melts and PVAs were used. The strength of the resultant bindings were measured by the flex test. Simple correlation coefficients relating each paper parameter to binding strength revealed that roughness was a significant factor in all cases, that thickness and stiffness were important for cold emulsion bindings, that pick strength correlated highly in some cases, and that density and ash content had significant negative correlation factors.

This study (Johansson and Mendel-Hartvig) is important because it suggested a model for test parameters, methods, and analysis, and because it, too, is in agreement with other reports. Korhonen and Perila ("Comparison of the strength of thread-stitched and adhesive bound books and the investigation of factors affecting the strength of the binding"[13]), for example, report that roughness, thickness, K&N ink absorbency, and wettability are related to binding strength for hot melts, and for PVAs the significant paper qualities are thickness, grammage, tension strength, tear resistance, and surface strength.

Leekley *et al* ("The relationship between paper properties and adhesive book binding behavior"[14]) investigated absorbency, hypothesizing that "binding depends upon the penetration of liquid adhesive into the intrasheet and intersheet void space in the edge of the clamped pad of book stock."[15] Every measure of absorbency Leekley used proved significant, confirming the hypothesis. Testing was performed by page pull.

Arnamo and Thyboll ("Investigation of the influence of paper properties on the strength of perfect bound books"[16]) used the flex test and bound the test books with PVA. They found pick resistance, roughness, and wettability to be of significance.

These studies indicate the paper parameters which have proved to contribute significantly to binding strength. Roughness and thickness are the only factors of significance common to all the studies. In addition there is a trend, noted by Johansson and Mendel-Hartvig, "that hot melts depend on surface roughness and dispersion adhesives on sheet thickness."[17]

This thesis extends the application of this body of literature to cover papers in the newsprint range of quality. In addition, it had been conjectured that a limiting point may be reached, in which the paper would fail before the binding, thus leaving the strength of the book binding totally dependent on the inherent strength (or weakness) of the paper. Again, to preview the conclusions, this limit was not reached in papers down to 25-pound basis weight and .0024" caliper.

An additional aspect of this study is the investigation of the effect of acidity. Newsprint, being primarily of groundwood composition, is rather acidic. Background material on acidity is presented in a later section.

Binding Testing

Another area of pertinent literature deals with measuring the strength of the binding. As pointed out by Seija Korhonen in "Factors affecting the strength of a book,"

> For practical purposes it is quite difficult, troublesome and slow to measure the use strength of a book. That is why it is inevitable to define the measurable strength properties which can be used to quantify the strength of a book. The measurable properties should as well as possible describe the use strength of the book and the use strains are to be simulated in the testing method. . . . The most common method of determining the strength of the block is undoubtedly the measuring of the pull and flex strengths of the leaves.[18]

Every study here cited used one or the other or a combination of both the page pull and flex test.

The pull test is accomplished by clamping the book block, usually flat, and pulling one page directly up until it pulls from the book. (See illustration, Figure 1.) The strength required to pull the page out is recorded. This is a static test of strength similar to tensile testing.

Page flexing, on the other hand, is a dynamic test. Flex testing fatigues the adhesive/fiber bond by flexing a page back and forth through 120°. (See illustration,

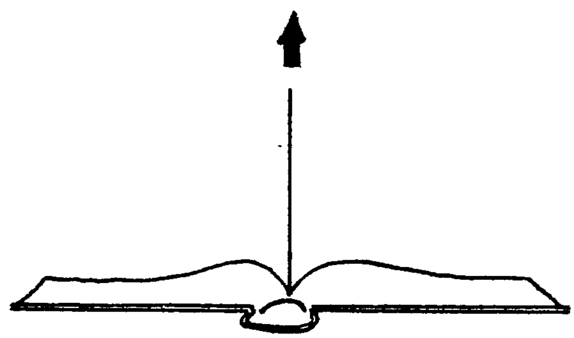


Figure 1.

Generalized schematic of the page pull test.

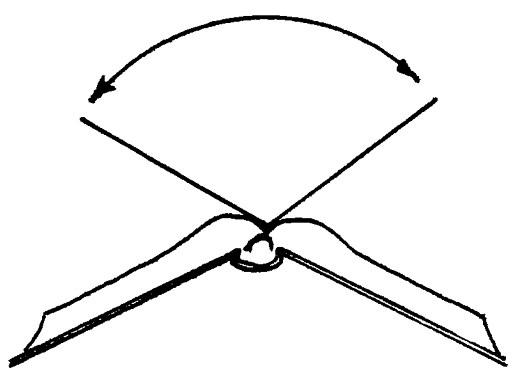


Figure 2.

Generalized schematic of the flex test.

Figure 2.) A minimal weight pulls the sheet, generally two pounds or one kilogram. The number of flexes before the page pulls out is recorded.

There is some controversy in the literature about these two tests because, as Lamb discovered in the very beginning, they do not correlate with each other.[19] Lamb did not consider the page pull very useful as it did not have significant effect on the quality of the binding.[20] Other researchers, such as Leekley et al and Korhonen and Perila, have obtained satisfactory results from page-pull. It is evident to this researcher that page pull and flex tests generally cannot be expected to correlate as they measure strength properties which are quite different from each other. The flex test worries and fatigues the fiber/adhesive joint until failure, while the page pull challenges the tensile strength of the weakest link. The weakest link evidently is the primary fiber/glue adhesion. Both page pull and flex test were used for this study.

Page pull and flex testing are not, however, the only tests available to researchers. Jack Bendror ("Technology and Testing of Library Bound Books") notes, "There are no universally accepted testing methods for determination of binding strength."[21] Bendror then lists, besides page pull and flex testing: corner pull; subway test; tumble test; openability; accelerated aging; and temperature stability. The Barrow Research Library finds another test, the "backbreaker," useful for spine testing.[22] All the researchers into paper factors limited themselves to pull and flex tests. The other tests listed above are often concerned with the durability of the book as a whole, or with comparative testing, the subject of the next section.

Comparative Testing

Mention should be made of the work done in comparing binding methods. Bendror's report covers the parameters involved, discussing various qualities as readability and openability as well as strength and durability.[23] The direction of his report is to encourage the formulation of an Optimum Binding Index, similar to Lamb's index, by which the library binding industry in particular could choose the best alternative to Class A bindings where Class A is not appropriate.

Stemming from Bendror's work and from interest by the Library Binding Institute are works by James Rich ("Cold Emulsion Polyvinyl Acetate Bindability Criteria,"[24] a Master's thesis at the Rochester Institute of Technology), and a work in progress by Caroline Watson and Werner Rebsamen on comparative testing of cleat lacing, double fan adhesive binding, and oversewing.

Acidity

Acidity as a factor affecting binding strength has not been tested. This oversight is not surprising in light of the findings of the W. J. Barrow Research Laboratory: "The amount of acidity found in a new paper has no effect on either its folding endurance or tear resistance at the time of testing."[25] The report adds, "However, acidity, even in small amounts does damage the molecular structure of cellulose and causes gradual and continued strength loss in papers as time passes."[26] Since acid is the most significant factor affecting change of paper strength over a period of time, and since newsprints have a relatively low pH (high acidity). acidity testing was included in this study.

The source of acidity is primarily the lignin in the groundwood. Chemical pulping neutralizes this source of acidity. Thus acidity is of greater concern in groundwood papers as opposed to "free sheets" which are free of groundwood.

Since the effects of acidity on paper quality occur only over a great deal of time, accelerated aging by heat must be used to simulate natural aging. As Barrow again points out, "Chemical activity proceeds, in general, faster at elevated than at lower temperatures."[27] Based on that knowledge, Barrow conducted experiments and reviewed literature on aging and concluded, "For a round figure, 25 years seems an acceptable equivalent value . . . of the generally used heat-aging cycle of 3 days at 100° C."[28] That figure is for paper and other cellulose fibers, and is inappropriate for testing synthetic binding material.

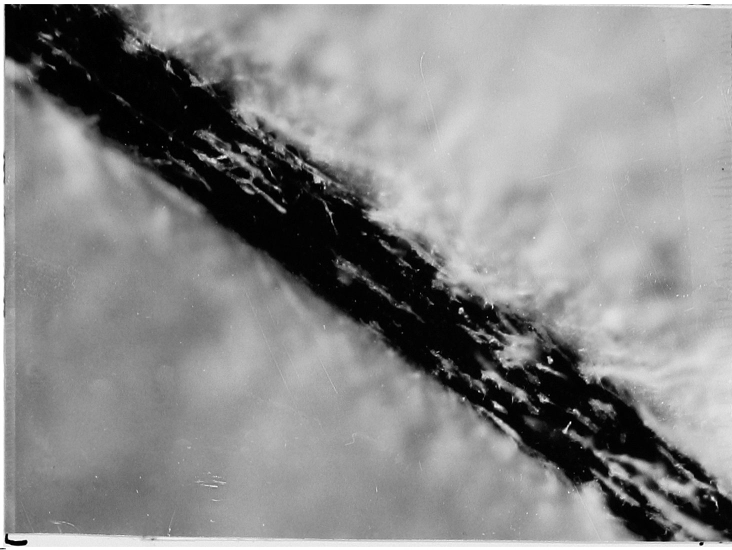
CHAPTER III

THEORETICAL BASIS

Inspecting paper through a microscope is perhaps the best way to understand the nature of the paper/adhesive interface. Under a microscope, the paper is no longer a discreet sheet, but a mat of fibers, more resembling a frayed doormat than a single sheet of paper. The model for the mechanical action by which the sheets are bound to the spine takes the fibrous nature of the sheet into account.

Preliminary hypotheses about the nature of the bond assumed that, once imbedded, the fibers pulled out evenly across the z-direction of the sheet, that is, across the thickness of the sheet. It was expected that an even distribution of fibers would be visible along the spine when several sheets were torn out. However, it was very evident when viewed under the microscope, that the fibers pulled out in orderly rows, and moreover the rows corresponded to the outside surfaces of the sheet. Please see Illustrations 1-3, page 20.

These illustrations are photomicrographs, at 30-power magnification, of a strip along the spine of an adhesive binding. Five sheets have been pulled from each sample. Close inspection will reveal five distinct dark bands



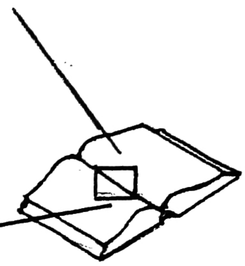


Illustration 1.

Photomicrograph under 30x magnification, showing adhesive binding where five sheets have been torn out.

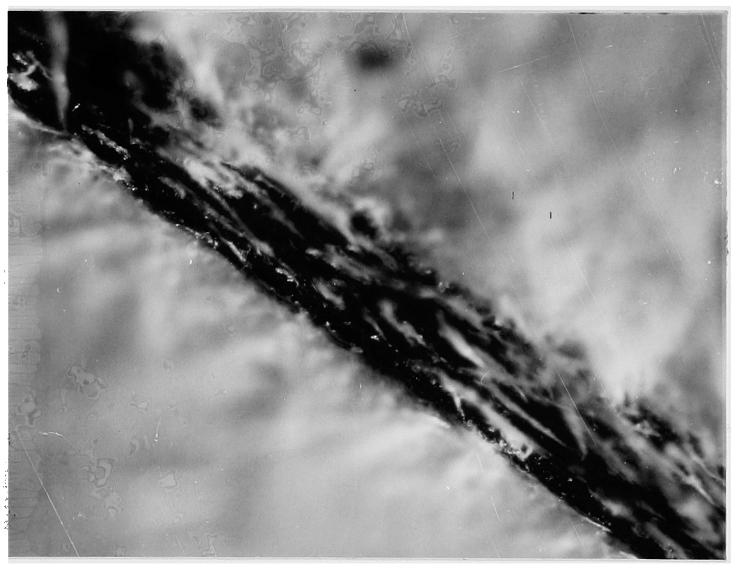


Illustration 2.

Photomicrograph under 30x magnification, also showing adhesive binding where five sheets have been torn out.

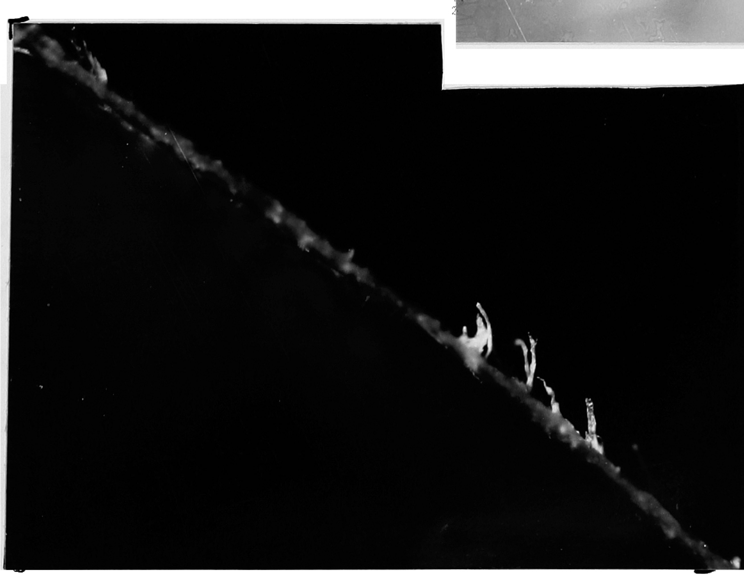


Illustration 3.

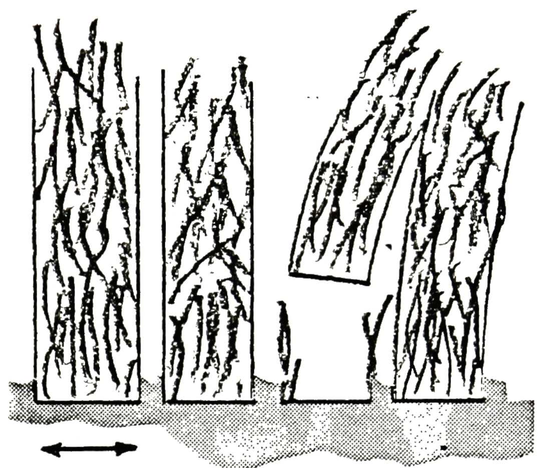
Single sheet under 30x magnification.

separated by a narrow, intermittent line of fibers. The five wide dark bands represent the five sheets pulled out; the fiber strips therefore denote the boundaries or surfaces of the sheets.

Although it is difficult to discern on the photographs, closer inspection would reveal a double row of fibers, suggesting a layer of fibers from one sheet and another layer from the sheet next to it. The third illustration (Illustration 3) shows a single sheet which has been pulled from the binding (again under 30-power magnification). The edge is still sharp, crisp, and untorn; relatively few fibers have been disturbed.

It appears, then, through microscopic inspection, that only the surface fibers are bedded in the adhesive firmly enough to pull free or "pick" from the sheet. Other fibers along the z-dimensions are held more firmly by the sheet, surrounded on all sides by fibers supplying the interfiber bond. Please see illustration, Figure 3 on page 22.

The model was adjusted to account for the information that surface fibers contribute to binding strength in a different manner than the inner fibers. The hypothesis based on this new model was that the surface fibers contribute strength because they bond so well with the adhesive. This contribution is in turn due to penetration by the adhesive into the intersheet spaces. Leekley et al adds that "intersheet porosity is a function of sheet roughness . . ."[29]



z-dimension

Figure 3.

Surface fibers remain bedded in the adhesive when the sheet is pulled out.

Penetration, and therefore binding strength, was hypothesized to be due to sheet roughness.

The contribution of the inner fibers was hypothesized to be measured by correlation of caliper with binding strength. That is, the contribution of the inner fibers would be in direct proportion to the thickness of the sheet; the thicker the sheet, the more the bonding, due to greater surface area in the z-direction.

All of the following hypotheses were based on the adjusted model of the fiber/adhesive interface just described. The hypotheses were tested by checking for correlation between each factor and binding strength. Binding strength was measured by flex test and page pull both before and after aging the paper. A discussion of the statistical analysis follows in the next section.

The factors under investigation were divided into three general categories of paper qualities: sheet strength, sheet characteristics, and other properties.

Sheet characteristics	Sheet strength	Other
Caliper	Tear resistance	Active acidity
Roughness	Internal bond	
Absorbency	Pick resistance	
Fiber composition	Tensile strength	
(Pick resistance)		

Each general group of paper properties reflects the different general sources of binding strength. The original model assumed sheet strength led directly to binding strength. Subsequent research and investigation revealed that, indeed, paper factors control binding strength, but it is not necessarily the <u>strength</u> of the sheet which is significant. The factors under "Sheet characteristics" were then hypothesized to be responsible for binding strength, as described below. Sheet strength was still investigated to insure that, with these lightweight papers, sheet strength is not after all a significant factor.

Roughness of the paper was hypothesized to be the most significant factor leading to a strong adhesive binding. Rough paper creates greater intersheet space so that the surface fibers are available to the adhesive. Every major test reviewed found roughness to be significant.

Sheet thickness (caliper) was not expected to be significant. It was hypothesized that roughness and caliper can be used to locate the primary bond either on the sheet's surface or on its z-face, respectively. If roughness proved significant, it would mean the surface fibers were responsible for the strength of the binding. If caliper proved significant, the source of the strength of the binding would be the inner fibers along the z-face. It was hypothesized that either one or the other (roughness or caliper) would prove significant. Roughness was hypothesized to be the more likely factor, based on the results of the reports reviewed in Chapter II.

Absorbency was also expected to correlate with binding strength, because absorption of adhesive into the top layer of fibers is the action by which it was hypothesized the binding takes effect. The absorption of hot melt is fairly limited because of its high viscosity, even at high temperatures. That is why the surface fibers were deemed more important then fibers deep in the sheet.

Tensile strength and tear resistance were not expected to prove significant, because they are measurements of gross sheet strength, and do not reflect the fiber qualities which lead to a good bond between adhesive and paper fibers. In addition, the literature indicated they would be relatively insignificant.

It was hypothesized that pick resistance and internal bond were similar tests measuring the strength of the interfiber bond. They were expected to correlate with each other and with binding strength, because the model assumed that binding strength depended on the fibers which became firmly bonded to the adhesive. It was subsequently discovered that pick resistance is not similar to internal bond. Pick resistance is a distinct quality, measuring the ease by which surface fibers lift or pick from the surface. (The trait may be visualized as "fuzziness" of the sheet.) Pick resistance evidently is not a measure of sheet strength, but belongs in the category with caliper, roughness, and absorbency.

It was hypothesized that a higher proportion of chemically pulped fibers would lead to higher binding strength, because chemically pulped fibers are longer and stronger than mechanically prepared fibers.

The effect of acidity was expected to be insignificant until accelerated aging had given the acid a chance to work its slow damage. The source of acidity is the lignin left in the mechanical pulp which is never neutralized chemically. Mechanical pulping is less expensive than chemical pulping, and so acidity is a factor in all cheap, mechanically pulped papers such as newsprint. The amount of acid is very small and yet over the course of time can considerably weaken any material, such as paper, made up of cellulose fibers. The method of measuring pH (acidity) in paper is discussed in Chapter IV, "Methodology."

Acidity was expected to correlate with change in binding strength (the difference between binding strength before and after accelerated aging). It was hypothesized acidity would be the major factor responsible for loss of binding strength with age.

Statistical Analysis

The correlation factor $\underline{r}$ is an expression of the extent two variables are related.[30] The value of $\underline{r}$ ranges from +1 to -1. Zero indicates there is no correlation; ± 1 means perfect correlation. The higher the absolute value of $\underline{r}$, the stronger the correlation.

The significance of the factor $\underline{r}$ depends on the number of samples taken. The factor $\underline{r}$, in order to be confidently interpreted as "significant," must reach a higher value as the number of samples (n) decreases. For n = 8, as in this study, r must reach $\pm.707$ to reach statistical significance. A chance of error is always present; limiting the chance of error (the alpha risk) also raises the value which r must reach to be significant. In this case, $\alpha = .05$. A higher risk, $\alpha = .10$, would lower the significance threshold of r to .6215.[32]

The equation for the correlation coefficient r is:[33]

$$r = \frac{\Sigma X_i Y_i - \dfrac{\Sigma X_i \Sigma Y_i}{n}}{\sqrt{\left[\Sigma(X_i^2) - \dfrac{(\Sigma X_i)^2}{n}\right]\left[\Sigma(Y_i^2) - \dfrac{(\Sigma Y_i)^2}{n}\right]}}$$

X_i = the values of a parameter, such as paper thickness for paper samples A through H. Y_i = the values of another parameter, such as strength, again for samples A through H. n = the number of paired samples; here n = 8

The null hypothesis in each correlation test is H_0: There is no correlation between two sets of data. Rejection of the null leads to H_1: there is evidence of correlation between the two sets of data. $\alpha = .05$ means that there is, in rejecting the null, a 5% chance of being wrong. This is the level of significance used in this report.

CHAPTER IV

METHODOLOGY

Summary of Procedure

Samples of paper actually used for mass-market paperback books and catalogs were obtained, and tested according to TAPPI (Technical Association of the Pulp and Paper Industry) procedures. Values were obtained for all the factors under investigation: caliper, tensile strength, internal bond, roughness, tear resistance, pick resistance, acidity, absorbency, and fiber composition. Average values and standard deviation for these tests are reported for the eight papers, A-H, in Appendix III. Descriptions of the tests follow this section.

Three books from each paper were made in one run on the same machine, using a commercially-available hot melt. To keep the variables to a minimum, no spine preparation was used; the backs were trimmed only. The books were all of a consistent trimsize and bulk. The binder was a Muller Pony Binder. The adhesive was heated to 375° F and applied in an ample coating to insure adequate coverage and film thickness, to minimize the effect of adhesive application variability. Paper covers were applied to simulate actual binding procedure.

The books were then tested for binding strength, using the page pull test and the flex test. Three pages were pulled and flexed from each book. Each measurement of strength was thus the average of nine samples (three pages from each book, three books of each sample paper). A high number of samples was required because the variability of values measured on these devices is quite high, and small differences in strength must be detected. The "standard deviation" is a measure of the variability of the samples and of the testing device. Nine samples statistically insures that the mean of the samples is within .75 of a standard deviation of the "true" mean (with an alpha risk of .05).[34]

The books were then heated for three days to age the paper. The temperature for aging paper (100° C) was inappropriate for aging the adhesive, which turned soft and soaked into the paper. The books were rebound following the same methods and precautions as the first binding. This aging procedure was for the sole purpose of testing the effect of acidity on binding strength. The books were retested for pull and flex values. The results of these tests (page pull before and after aging and flex test before and after aging) as well as a measure of the change in binding strength (the difference between the "before" and "after" values) are presented in Appendix III.

The paper factors were tested for correlation with each other and with binding strength as measured by page pull and flex testing. The results of these correlation tests are presented in Appendix IV. The results of the binding tests were tested for correlation with each other and are presented in Appendix V. Correlation factors below .500 are represented by "ns" for "not significant;" factors above ±.707 are underlined to portray statistical significance. The correlation data is presented in graph form in Appendix VI. Interpretation of these charts is presented in Chapter V, "Results."

<u>Description of Tests</u>

Data from these tests is presented in Appendix III, along with standard deviation values. The standard deviation (s) is a measure of the variability of the sample and the test apparatus.

1) Thickness or caliper was measured by a motor-driven micrometer, according to TAPPI (Technical Association of the Pulp and Paper Industry) Standard T411. A single sheet at a time is measured, and several readings are taken for each final value. Units reported in Appendix are thousandths of an inch.

2) Tensile strength was measured according to TAPPI T404. Specimen strips of constant width were put under increasing tensile strain until they failed. The maximum strain, indicated by a pointer on the pendulum, is the tensile strength, in kilograms.

3) Internal bond strength was tested on a Scott

internal bond tester according to TAPPI Useful Method 403. The paper specimen is bonded on both sides by double-sided adhesive tape. The specimen is fixed to a horizontal base, and a metal bar with a vertical tab is fixed on top. A pendulum strikes the tab parallel to the surface of the paper. The impact results in delamination of the paper, and a pointer indicates in thousandths of a foot-pound the force required.

4) Roughness was measured on a Sheffield smoothness instrument. Specimens $3\frac{1}{2}$" x $3\frac{1}{2}$" are placed on a glass plate. The testing head is gently lowered onto the paper. Compressed air escapes from the head over the surface of the paper and is measured on a flowmeter (a float indicator in a column), Units are Sheffield units. This procedure follows TAPPI Useful Method 518. Measurements were taken from both sides of each sample and averaged. Although the test is called a "smoothness" test, higher values mean greater roughness. For the sake of simplicity in correlating the data, the values were designated "roughness."

5) Tear resistance was measured according to TAPPI T414 by an Elmendorf tear tester. Sixteen sheets are clamped in the tearing machine and are slitted to start the tear. A pendulum supplies the force to tear the sheets; the force required is measured by loss of potential energy indicated by a pointer. Units are in grams. Tear testing was carried out across the grain only, because the books

are bound grain short.

6) Pick resistance (or surface strength) was measured by Dennison wax pick test according to TAPPI standard T459. Calibrated sealing waxes are applied to the specimen and pulled off. The paper specimen is then inspected at an oblique angle for any evidence of disruption of the sheet or fiber picking. The rating of the paper is the highest number of wax in the series that does <u>not</u> pick or pull fibers away from the paper. Average values are reported in Appendix III.

7) Acidity was measured using a pH meter and the cold extract method according to TAPPI Useful Method 440. One gram of paper, cut in small squares, is soaked for an hour in 50 ml. of distilled water. The unfiltered mixture is then measured on the pH meter. For purposes of correlation, the values of pH were translated from the logarithmic pH scale to a normal scale. Every step of 1.0 away from the neutral value of 7.0 on the pH scale represents a 10-fold increase in "active acidity." Thus for this study acidity is reported in values of "active acidity" translated from the pH scale. For example, pH 7.0 = 1; 6.5 = 3; 6.0 = 10; 5.1 = 80; and 5.0 = 100.[35]

8) Ink absorbency was measured by the K&N test. A portion of the K&N ink mixture is placed on the paper sample for a specified amount of time. The mixture is then wiped off, and measured for density on a densitometer. The higher the

optical density, the greater the absorbency. The densitometer is calibrated to zero on the paper.

9) Fiber identification was carried out by preparing slides of the samples for inspection by microscope. Stained with "C" stain, the mechanically pulped fibers appear fragmented and yellow; the chemically pulped fibers are whole and very pale yellow-gray or clear. The number of each kind of fiber is counted across the width of the viewing area; several areas are counted. The proportion of chemical fibers to total fibers was expressed as percent fiber composition.

10) The page-pull test was performed on an Instrom motor-driven tensile testing device, Model 1130. This model has jaws to clamp both the book and the single page to be pulled out. The book is clamped back-to-back, <u>without</u> breaking the spine; the pages fan out as the spine is rounded. A single sheet is pulled upward until failure, and the weight required is recorded by pen on graph paper (in 1/4-kilogram units). This device is very sensitive and consistent.

11) Flex testing was carried out on a Kolbus Flex-Tester, type FT. The book is clamped open to 240°, without breaking the spine. A single page at a time is clamped and flexed back and forth through a total of 60°. The page is under a constant tensile load, 200 grams in this case. Care must be taken to insure that the arc of the flex is centered on the spine and that the sheet pivots from the

spine. Books with poor openability tend to give unreliable results.

CHAPTER V
RESULTS

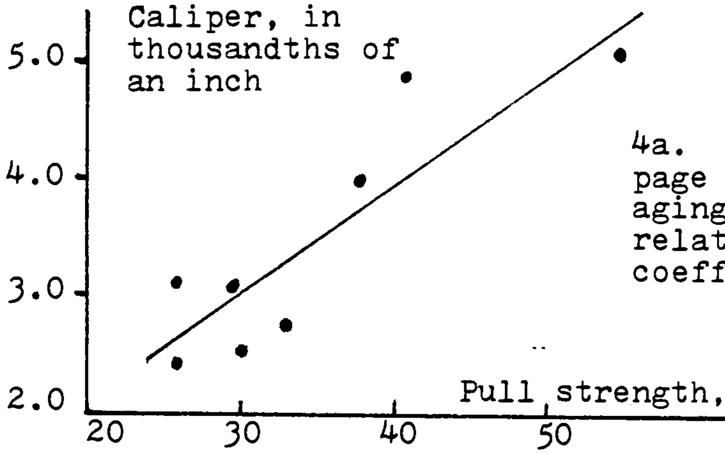
Tests for this study were carried out in two areas: testing of the paper parameters, and testing of binding strength. The data from these tests is presented in Appendix III. Before further analysis of results, it should be noted that, although some critical limit to binding strength due to sheet failure was hypothesized, no limit was reached in the papers in this study (minimum 25-lb basis weight and .0024" caliper). The average page-pull value was 19 pounds, or 2.7 lbs/linear inch (the books were seven inches tall). The values ranged from 2 lbs/linear inch to 4.25 lbs/linear inch. Muller-Martini quotes a standard by which 2.5 lbs. and below rates "poor;" over 4.1 is "excellent."[36]

From this data in Appendix III simple correlation coefficients (r) were computed for each pair of variables. The results of the correlation analysis are presented in Appendices IV and V. A graph of the same information is presented in Appendix VI. This graph shows a vertical scale for correlation figures from +1 to -1. The dotted line at $r = \pm.707$ shows the cutoff for statistical significance, alpha = .05 and n = 8 (the number of paired samples used in the correlation computation).

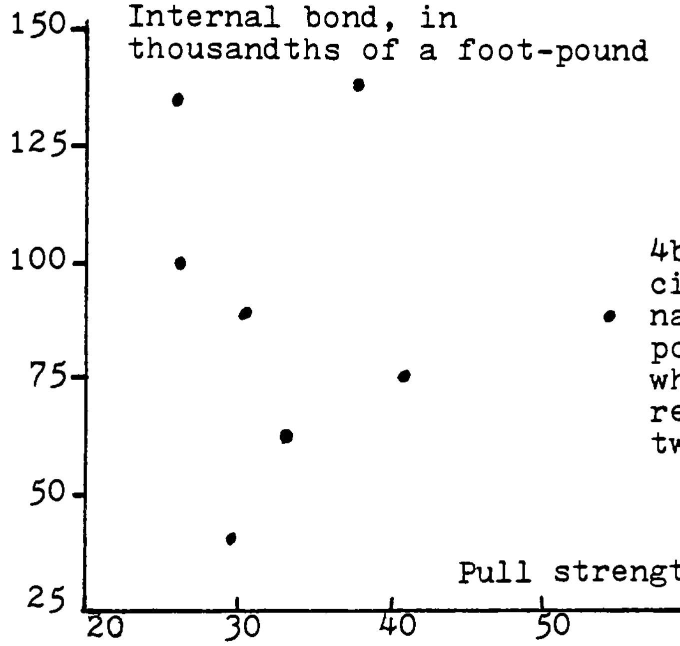
Lower values than $\pm.707$ are not meaningless, however. At the price of a greater risk of being wrong in concluding "significance" the threshold could be dropped to r = .6215. The alpha risk at that level would be .10, or a 10% chance of being wrong if the factor were interpreted as having significant correlation. Figures in this area can be termed as "approaching significance." The conclusions of this study are all based on interpretation of these charts of correlation coeffecients.

By way of explanation, the first column on the graph (Appendix VI) is for the page pull test, before aging. The scale on the right edge of the page is values of correlation (r). Above zero is positive correlation, below is negative correlation; both negative and positive correlations can be significant. Pertinent correlation values from Appendix IV have been transferred to this chart (Appendix VI). Thus the correlation of page pull with caliper, which is +.883, appears near the top of the column, above the .707 cutoff. Figure 4, page 37, clearly shows the relationship that is signified by "correlation."

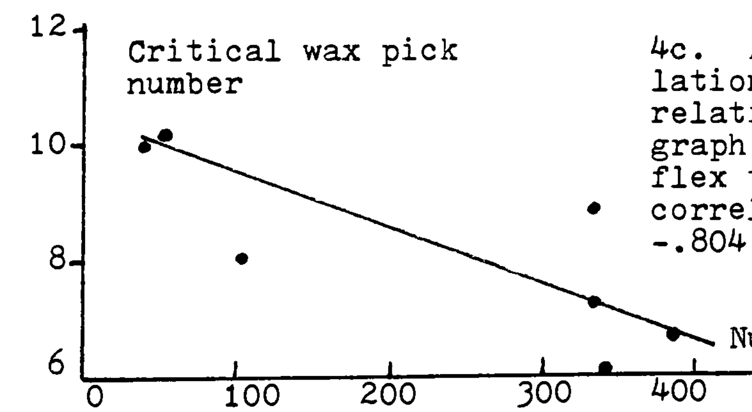
The graphical presentation (Appendix VI) clearly portrays that caliper outweighs all the other factors, reaching statistical significance in three out of four columns. The hypothesis that roughness would prove more significant than caliper is clearly mistaken; the results show that for these lightweight papers the thickness of the sheet has



4a. The graph of caliper vs. page pull strength before aging shows a clear direct relationship. Correlation coefficient r = .883.



4b. The correlation coefficient of page pull and internal bond is -.093. The graph portrays the random pattern which signifies there is no relationship between the two factors.



4c. A strong negative correlation signifies an inverse relationship. This is the graph of pick resistance vs. flex test before aging; correlation coefficient r = -.804.

Figure 4.

become the critical factor. Binding strength is proportional to the surface area along the z-direction of the sheet.

Roughness evidently does not contribute to the facility with which fibers are bonded to the adhesive. Roughness seems to achieve what little significance it has (.546) because it correlates with other parameters which do correlate with binding strength (caliper, absorbency, and low pick resistance). It had been thought that roughness would contribute to greater penetration of adhesive between the sheets, and thereby to a greater bond of the surface fibers. Microscopic investigation had shown that the surface fibers were indeed bonded more strongly to the adhesive.

It now appears that low pick resistance ("pickability") and not roughness is responsible for the bonding observed under the microscope. Low pick resistance means that the surface fibers are easily picked from the sheet. Pick resistance reached a significant negative correlation with the flex test (-.804) and approached significance with the page pull (-.679). The negative correlation implies that a paper which "picks" (or which has fibers readily available at the surface) contributes to binding strength. It must be concluded that the availability of the fiber to the adhesive is a critical factor, and that "pickability" and not roughness creates that availability. Thus "pickability" (negative pick resistance) correlates highly with both measures (flex and pull) of binding strength.

The results of caliper, roughness, and pick resistance indicate that strength of adhesive bindings depends on availability of fibers to the glue. In other words, the greater the fiber surface area exposed to the glue, the stronger the resultant bond. Evidence from the remaining factors corroborates this effect.

Absorbency approached significant correlation with the page pull test (.676). Absorbency, having the effect of drawing the adhesive further into the sheet, would increase the area of contact between fiber and adhesive. The significance of absorbency is consistant with the finding that the amount of contact between glue and fibers is more important than the inherent strength of the sheet.

The strength of the sheet itself was measured by three tests: tensile strength, internal bond strength, and tear resistance tests. None of these measures of sheet strength reached significant positive correlation with binding strength. In general it may be concluded that the strength of a sheet of paper has little effect on the strength of the binding, for the uncoated groundwoods used.

Further examination of the chart (Appendix VI) shows that fiber composition has no significant correlation with any parameter or measure of strength. In this study no evidence was found that the addition of chemically pulped fibers appreciably changes any of the measured properties of the sheet or the strength of the binding.

Active acidity, likewise, did not even approach significant correlation with any test of binding strength. It had been hypothesized that acidity would cause a deterioration of sheet strength and therefore binding strength. In that case, active acidity would have correlated with "change in strength." Active acidity did not correlate with change in binding strength. Considering the finding that the strength of a sheet (as measured by tensile strength, internal bond strength, and tear resistance) has nothing to do with the strength of the binding, it is no surprise that acidity proved insignificant.

Pick resistance and internal bond proved to be measures of different properties. The low correlation of the wax pick test (pick resistance) with the internal bond test (delamination resistance) shows that the pick resistance of the surface fibers bears no relation to the force required to delaminate the sheet.

Comparing pull testing to flex testing to discover possible advantages of one over the other, it should first of all be noted that the two correlated very well with each other. The values for *r* ranged from .653 to .950 (for correlation between page pull testing before and after aging and flex testing before and after aging--see Appendix V). Since the two types of testing are in agreement it is difficult to judge which of the two is a more discerning test. As for consistency and operator variability, the page pull test is more reliable; the flex test is subject to too many operator variables (such as clamping the book block, centering the spine on the flexing arc, and ensuring a full flex angle without breaking the spine). As evidence of the problem, the standard deviations (s) for flex testing are proportionally much greater than the standard deviations of the pull tests (see Appendix III). Despite these sources of variability, the flex test as well as the page pull test proved to be a helpful tool for analyzing the factors contributing to binding strength.

The testing procedures for the paper characteristics were also generally consistent and reliable. The wax pick test and fiber composition analysis both require experienced judgement but yielded reliable results.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Paper is made of fibers. This investigation has examined the adhesive binding of paper to discover how fiber characteristics account for the variability in binding strength. The efforts of this research were concentrated on relating measures of strength of the paper to strength of the resultant binding. To simulate the problems of economical binding styles, newsprint grade paper and hot melt adhesives were studied.

Nine properties of paper were investigated. These qualities were at the outset divided into three categories, as listed below. The groupings express the general factors involved. The specific characteristics within each group reflect attempts to locate the specific source of binding strength.

Sheet strength	Sheet characteristics	Other factors
tensile strength	caliper	acidity
tear resistance	pick resistance	
internal bond	roughness	
(pick resistance)	absorbency	
	fiber composition	

Although the hypotheses assumed that a strong interfiber bond would lead to a strong binding, it was found that the most critical factor was not the strength of the sheet (measured by factors in the first column). but the availability of the fibers to the sheet (reflected by factors in the second column).

The strength of the sheet was measured by several tests. These tests were: tensile strength, internal bond, tear resistance, and pick resistance. These tests were thought to be various measures of the interfiber bond; the tests which best measured interfiber bond were expected to correlate with binding strength. To the contrary, none of these tests showed significant positive correlation with binding strength. This finding leads to the conclusion that the inherent strength of the paper is not important to the strength of the binding, even for lightweight newsprint-grade papers.

The other tests performed on the paper were designed to reveal more about the nature of the fiber/adhesive interface. These tests were: caliper (or thickness), roughness, and absorbency. Although roughness was expected to be the most important factor leading to a strong binding, caliper proved to be without question the most significant factor for these newsprint-grade papers.

Greater roughness was supposed to lead to more fibers bonding with the adhesive, as the adhesive penetrated between the sheets. Visual inspection under magnification affirmed the assumption that the surface fibers made a distinct contribution to the strength of the binding. Previous studies also indicated roughness would be significant. However, there was no evidence in this study that roughness even approached making a significant contribution to binding strength. Evidently, the contribution of the surface fibers is not a result of roughness.

Absorbency, however, did contribute to binding strength. Absorbency contributes to a thorough physical contact between the fibers and the glue. The amount of physical contact between the surface fibers and the adhesive is evidently a significant factor in the strength of an adhesive binding.

Caliper or thickness was the most significant factor contributing to the strength of a binding. This finding implies that the greater the surface area exposed to the glue film, the stronger is the total bond holding the sheet to the spine. In other words, the thicker the sheet, the better the binding for these uncoated groundwood papers.

The general conclusion that the greater the exposure of fibers, the stronger the binding, is confirmed in an unexpected way. Pick resistance proved to have a significant <u>negative</u> correlation with binding strength. It must be concluded that the quality described as "low pick resistance" contributes to binding strength. A sheet described as having "low pick resistance" would have fibers readily available at the surface both to the wax in the wax pick test and to the glue in binding.

These findings compel an adjustment to the model. The model upon which the hypotheses were based indicated that the bonding of the surface fibers was the major source of binding strength, and roughness in turn made the greatest contribution to bonding of the surface fibers. As this investigation now indicates, the surface fibers do indeed contribute significantly to binding strength (although low pick resistance and not roughness is the source of the contribution). But caliper proved even more significant. The general conclusion, upon which the adjusted model is based, is that binding strength depends on the amount of contact available between the glue and the sheet. This general requirement is fulfilled by a combination of factors. The leading factor is caliper of the sheet, which is a measure of the surface area presented to the glue along the z-face or edge of the sheet. Also contributing to greater contact is absorbency and low pick resistance, which are measures of how readily the fibers are available to the liquid glue. Thus for these uncoated groundwood papers, a good indicator of resulting binding strength would be the thickness of the sheet and the reaction of the paper to pick testing. It may be said that the wax pick test, being an application of a melted solid, is comparable to the action of hot melt adhesive and thus gives a good indication of the "bindability" of the paper.

These findings indicate that any means of increasing the fiber/adhesive contact should lead to stronger bindings. Further study should concentrate on specific spine roughening techniques for different grades of paper to find the most appropriate method of exposing more fibers to the adhesive.

As for the effect of acidity, there was no evidence that acidity contributes to deterioration of binding strength. The papers suffered evenly the effects of aging; a highly acidic sheet did not suffer more than more neutral sheets. It had been thought acidity, by attacking the fibers and reducing the strength of the sheet, would also reduce binding strength. Considering the findings stated above, that the strength of the sheet is not related to strength of the binding anyway, it comes as no surprise that acidity has no demonstrable effect on adhesive binding strength, even over time.

This study of the effect of paper quality on adhesive binding strength has attempted to describe the action by which paper is bonded in an adhesive binding. Hopefully this investigation will contribute to a thorough understanding of the demands made on an adhesive binding due to the fibrous nature of the sheet. Bindery managers, adhesive manufacturers, and paper manufacturers may benefit from this information.

Constant investigation is required to maintain the best combination of materials and techniques. There is also a clear need for standardized testing methods and standards of binding strength.

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APPENDIX I
A DISCUSSION OF ADHESION

An adhesive is a material which becomes stiff when it changes from a liquid phase to a solid, thereby forming a film of adhesive which is bonded to the materials being held together (the pages of a book, for example).

Surface forces (adhesion) and the internal strength of the adhesive film (cohesion) cause the materials to be held together by the film of adhesive.

Adhesive forces are molecular forces which appear at the interfaces of materials being glued and allow molecules of different materials to adhere together. Thus, they act between materials of different kinds.

Adhesive forces work externally as so-called bonding forces on the materials being glued together. Roughening increases specific adhesion and enhances mechanical and specific adhesion. In bookbinding, adhesion problems outweigh all others.

Cohesion represents the sum of all intermolecular forces in similar substances which are responsible for the internal cohesiveness of a body.

Source: Muller Martini manual, "Perfect Binding: Theory and Principles," compiled by A. Schmid, p. 24.

APPENDIX II
GRAMMAGE CONVERSION

1. Basis weight = weight in pounds of 500 sheets of paper in the "basic size." There are several basic sizes:
   - cover: 20 x 26 inches
   - book: 25 x 38
   - bond: 17 x 22
   - newsprint: 24 x 36

   Book size was the basic size used in this study.

2. Grammage = weight in grams of one sheet of paper, 1 meter x 1 meter.

3. Conversion of basis weight to grammage:

$$\frac{\text{weight in pounds}}{\text{area in square inches}} \times \frac{\text{grams/pound}}{\text{square meters/sq. inch}}$$

$$= \text{grams/square meter}$$

$$\frac{\text{basis weight}}{\text{basic size x 500}} \times \frac{\text{454 grams/pound}}{\text{.000645 sq. meters/sq. inch}} =$$

$$= \text{grammage}$$

   For book paper, basis weight x 1.48 = grammage.

4. Conversion of grammage to basis weight (book basic size):

   grammage x .675 = basis weight

APPENDIX III
RAW DATA

	"A"	"B"	"C"	"D"	"E"	"F"	"G"	"H"
1. Caliper	4.86	3.98	3.08	2.38	2.75	5.06	2.54	3.08
s	.15	.08	.11	.05	.15	.25	.05	.05
2. Tensile strength	2.52	1.87	2.96	2.04	1.83	2.62	1.20	1.46
s	.24	.24	.36	.30	.08	.53	.16	.10
3. Internal bond	75.0	138.0	99.4	131.7	62.6	82.9	84.5	40.1
s	11.8	16.9	15.2	20.2	3.7	7.2	16.9	2.5
4. Roughness	308.4	243.2	108.9	100.3	125.7	178.8	177.4	86.8
s	13.4	22.5	17.3	11.3	15.3	17.4	17.0	6.3
5. Tear resistance	26.4	37.4	21.9	20.1	29.0	35.5	25.1	32.6
s	.3	2.2	.8	.7	1.5	1.2	1.3	1.2
6. Pick resistance	6.2	8.1	10.0	10.2	8.8	6.7	7.3	7.3
s	.8	.5	.6	.6	1.4	.5	1.2	1.0
7. pH (acidity)	5.44	5.71	5.41	5.08	6.08	5.44	5.46	5.13
s	.13	.03	.18	.08	.06	.01	.02	.03
Active acidity	37	20	40	82	8	37	35	76
8. Absorbency	.432	.410	.352	.326	.370	.413	.418	.358
s	.019	.012	.020	.028	.029	.018	.050	.066
9. Fiber composition	33.4	43.0	54.8	30.6	34.4	28.7	40.0	25.6
s	7.9	9.8	3.5	7.5	4.9	15.1	2.4	6.7
10. Page pull	40.5	37.6	25.9	26.0	33.1	54.2	30.2	29.5
s	5.5	3.2	4.8	8.3	1.9	9.4	.4	4.2
11. Page pull after aging	35.1	25.1	20.9	18.5	21.5	42.4	18.7	23.2
(s)	6.6	5.3	5.3	4.5	4.0	7.9	3.5	4.1
12. Flex test	341	105	41	52	334	386	544*	315
s	148	62	21	37	228	201	331	84
13. Flex test after aging	142	76	58	16	81	342	60	38
(s)	128	38	17	4	42	91	30	13
14. Change in pull strength	-5.4	-12.5	-5.0	-7.5	-11.6	-11.8	-11.5	-6.3
15. Change in flex strength	-199	-29	+17	-36	-173	-44	-484*	-277

*Unreliable. Not included in correlations

For a description of these tests and units of measurement, see text pages 30-34.

APPENDIX IV
CORRELATION COEFFICIENTS (r)

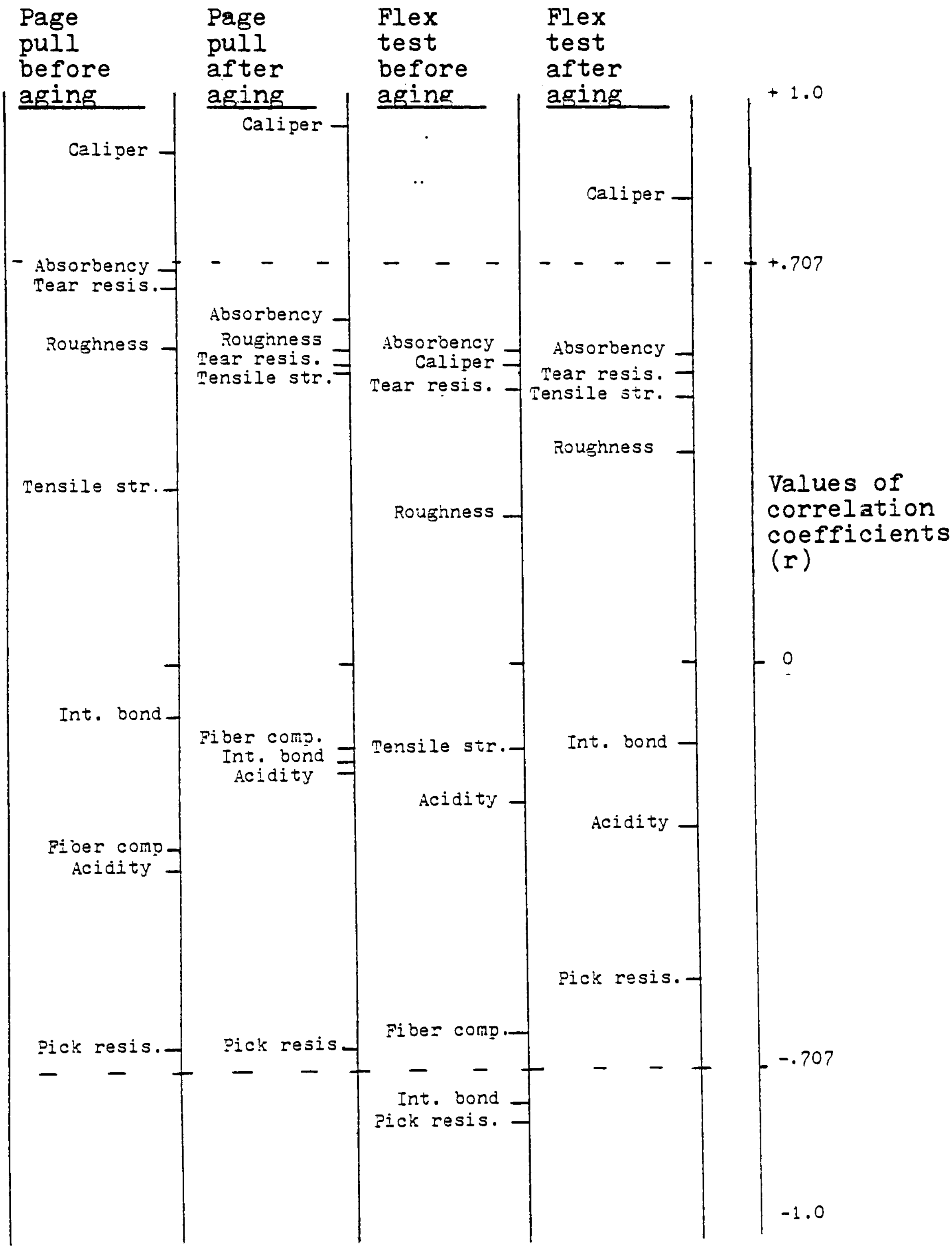
	Caliper	Tensile strength	Internal bond	Roughness	Tear resistance	Pick resistance	Active acidity	Absorbency
1. Caliper	--	.526	ns	.707	.562	-.683	ns	.683
2. Tensile strength	.526	--	ns	ns	ns	ns	ns	ns
3. Internal bond	ns	ns	--	ns	ns	ns	ns	ns
4. Roughness	.707	ns	ns	--	ns	-.633	ns	.861
5. Tear resistance	.562	ns	ns	ns	--	-.554	ns	ns
6. Pick resistance	-.683	ns	ns	-.633	-.554	--	ns	-.833
7. Active acidity	ns	ns	ns	ns	ns	ns	--	-.569
8. Absorbency	.683	ns	ns	.861	ns	-.833	ns	ns
9. Fiber identification	ns	ns	ns	ns	ns	ns	ns	ns
10. Page pull	.883	ns	ns	.546	.662	-.679	ns	.676
11. Pull, after aging	.952	.502	ns	.545	.519	-.685	ns	.600
12. Flex test	.527	ns	-.773	ns	ns	-.804	ns	.546
13. Flex, after aging	.811	ns	ns	ns	ns	-.562	ns	.544
14. Change in pull strength	ns	ns	ns	ns	-.563	ns	.569	ns
15. Change in flex strength	ns	-.588	-.813	ns	ns	-.538	ns	ns

APPENDIX V
CORRELATION COEFFICIENTS (cont.)

		Page pull	Pull, after aging	Flex test	Flex, after aging	Change in pull strength	Change in flex strength
10.	Page pull	--	.942	.653	.950	ns	ns
11.	Pull, after aging	.942	--	.666	.925	ns	ns
12.	Flex test	.653	.666	--	.609	ns	.677
13.	Flex, after aging	.950	.925	.609	--	ns	ns
14.	Change in pull strength	ns	ns	ns	ns	--	ns
15.	Change in flex strength	ns	ns	.677	ns	ns	--

Correlation coefficients (r) below ,500 are represented by "ns" for "not significant." Factors reaching statistical significance (above .707) are indicated by underlining.

APPENDIX VI
GRAPH OF CORRELATION DATA



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